Progress in Hybrid Particle Simulation of ICF Physics

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Outline

- Description of Hybrid Particle Simulation Capability in LSP.
- Examples of ICF Physics Modeling Progress.
  - Hohlraum Physics
    - Collisional absorption by photon ray-tracing
    - Hot electron production by LPI
  - Target Physics
    - Hybrid simulation of target compression by radiation drive.
    - Binary fusion reactions included in LSP.
- Conclusions

Massively parallel Hybrid-PIC code LSP bridges gap between PIC and MHD for ICF plasmas.

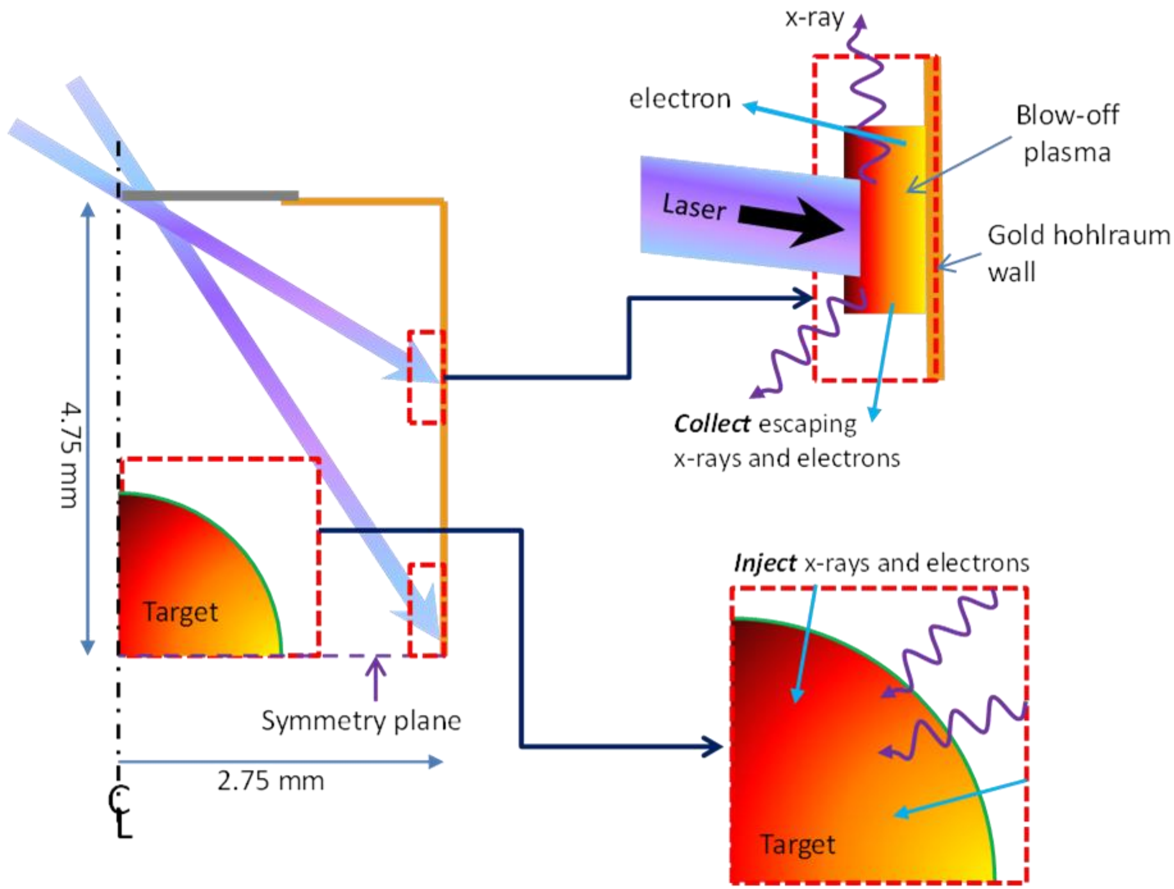
PIC methods are applied to particles using several different descriptions or equations of motion.

- Kinetic, multi inertial fluids, quasi-neutral MHD-like fluid with increasing level of approximation.
- Because all species are particles, migration from one EOM to another is seamless.
- Interactions between all particle descriptions (including fusion reactions) can be treated with fluid-like or binary (Monte-Carlo) methods.
- Charge-conserving EOS/radiation physics.
- The particle number per cell of all descriptions is controlled with Adaptive Particle Management technique.

ICF physics simulation capability rapidly improving

- Fully electromagnetic, relativistic platform with kinetic and fluid particle-in-cell treatments.
- Dynamic hybrid technique for transition from quasi-neutral or inertial fluid to kinetic.
- Photon ray tracing capability for laser heating.
- Radiation transport and drive package for hohlraums.
- Multiple material equation of state.

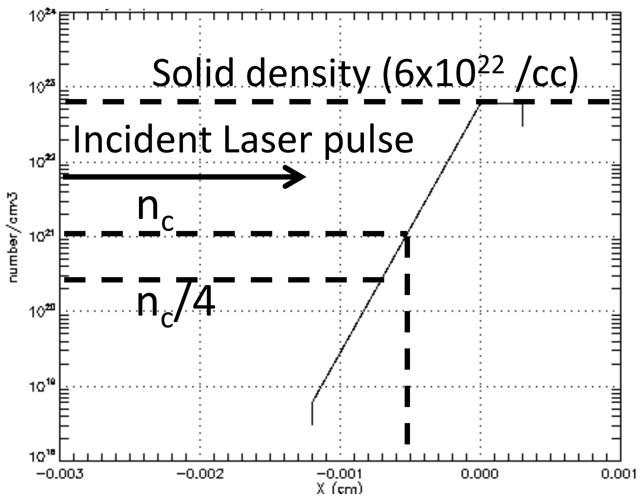
Hybrid capability can be applied to NIF Hohlraum, cross benchmarking



In the following slides we illustrate simulation results of Hohlraum and target physics.

PIC Formulation of Ray-Tracing Algorithm for Collisional Absorption

Singly-stripped Al plasma, λ = 1 μm



Collisional absorption can be modeled by the use of macro-particle photons which obey Lagrangian (Eikonal) equations of motion [1]:

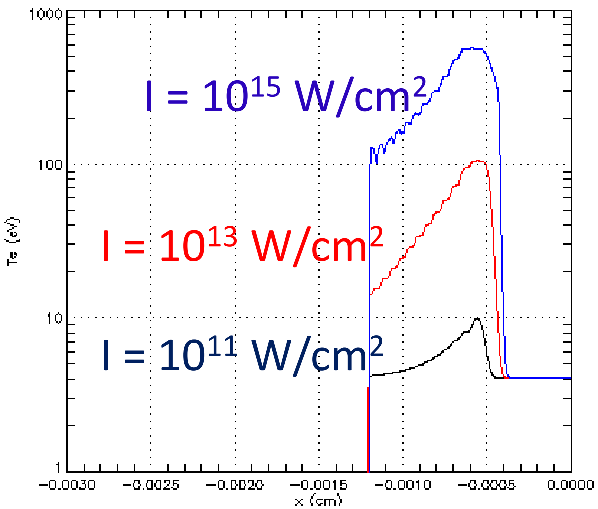
$$\frac{d\vec{x}}{dt} = \vec{v}_g, \quad \frac{d\vec{v}_g}{dt} = -\frac{c^2}{2}\frac{\nabla n_e(\vec{x})}{n_c}.$$

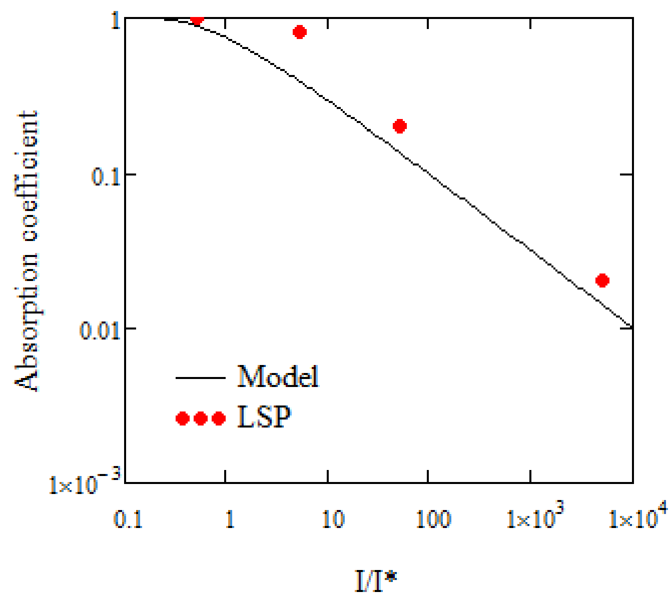
Macro-photon energy density is depleted along the ray trajectory [2] as:

$$\frac{du}{dt} = -\nu_{ei}\frac{n_e(\vec{x})}{n_c}u$$

and absorbed by the electrons (which then generate X-rays). This treatment does not require resolution of the photon wavelength.

Electron temperature at t = 5 ps





Model [3]:

$$A = 1 - \exp\left[-\frac{I^*}{AI}\right]$$

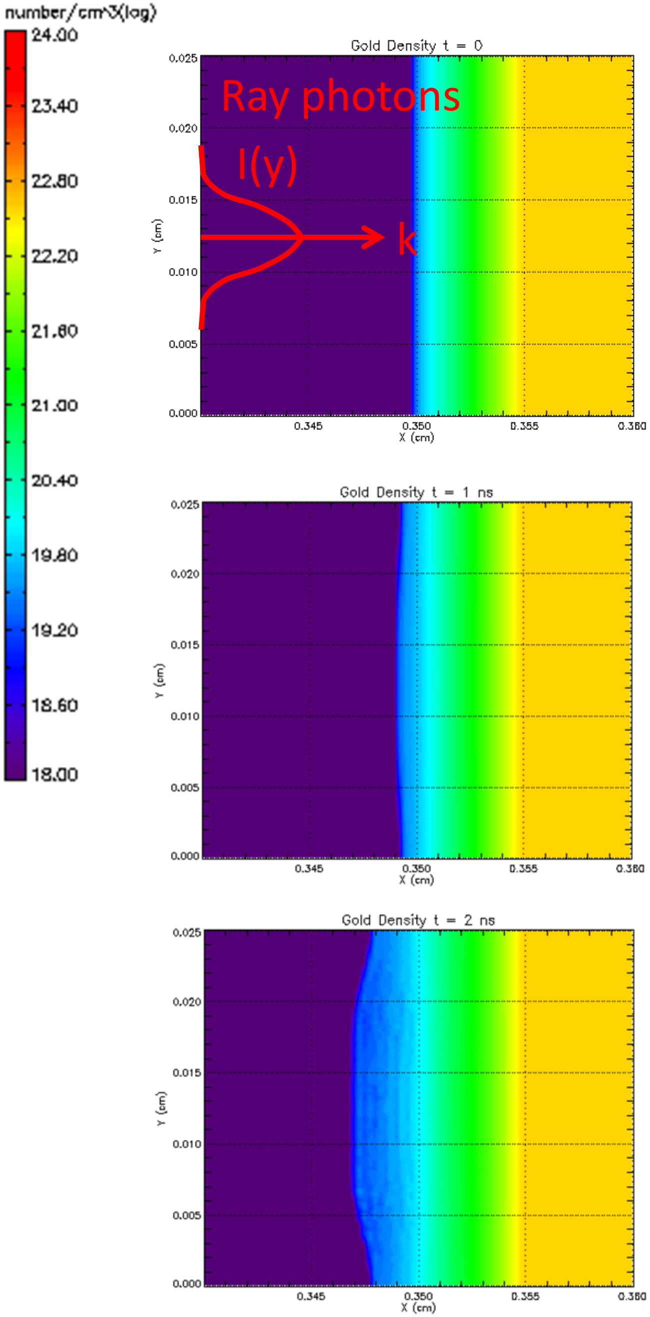
where

$$I^* \simeq 1.5\times10^{10}\,\frac{\mathrm{W}}{\mathrm{cm}^2}\,\frac{ZL}{\lambda^4}$$

L : density gradient scale length

[1] T.B. Kaiser, "Laser Ray Tracing on an Unstructured Three-Dimensional Grid" PRE **61** 895 (2000).
[2] W. L. Kruer, "The Physics of Laser Plasma Interactions", Westview Press, 2003.
[3] S. Atzeni and J. Meyer-Ter-Vehn, "The Physics of Inertial Fusion", Oxford University Press, 2004.

2D Simulations of Collisional Absorption in Gold Hohlraum Wall



NIF-like lasers parameters:

Peak intensity I= 10^{15} W/cm^2

λ = 1/3 μm (n_c = 10^{22} cm^{-3})

1-ns linear temporal ramp

Periodic boundaries in *y*

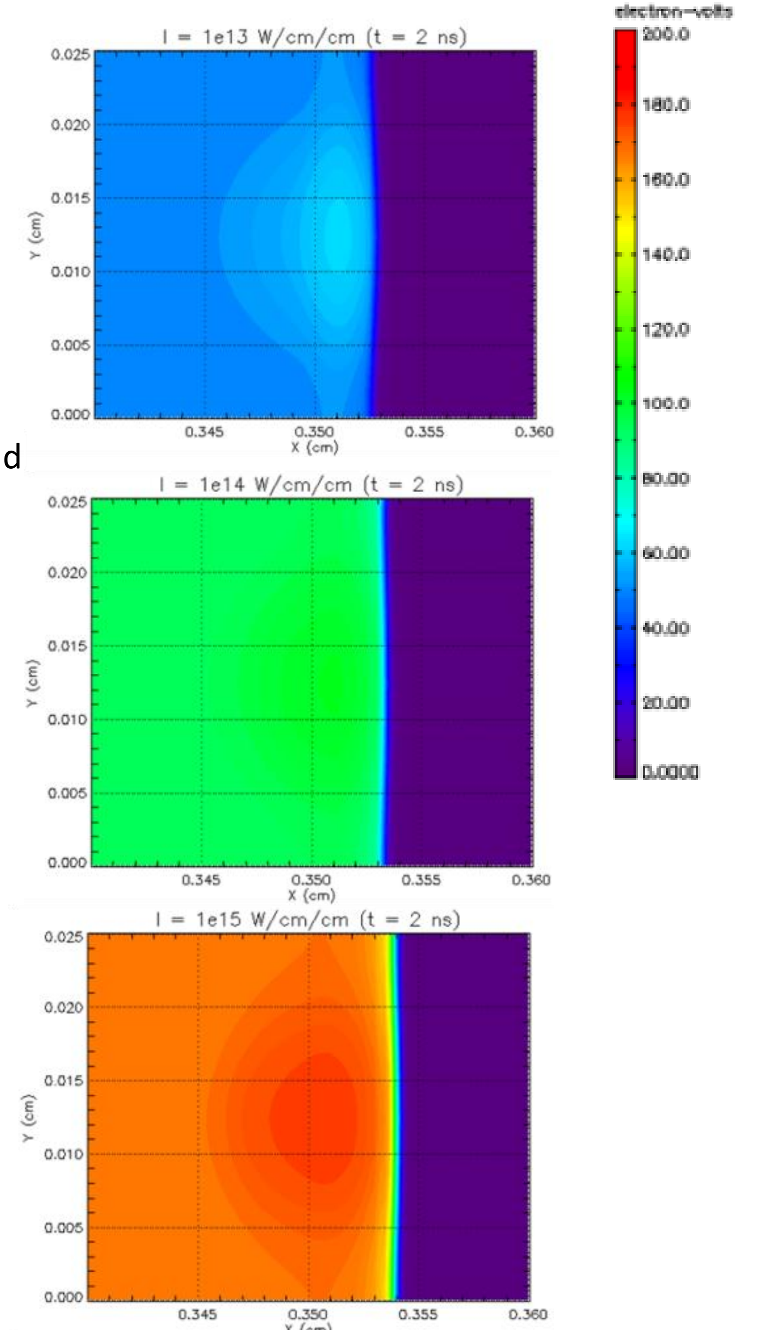
Gold EOS table and gray radiation diffusion coupled to plasma.

Quasi-neutral description of Gold plasma

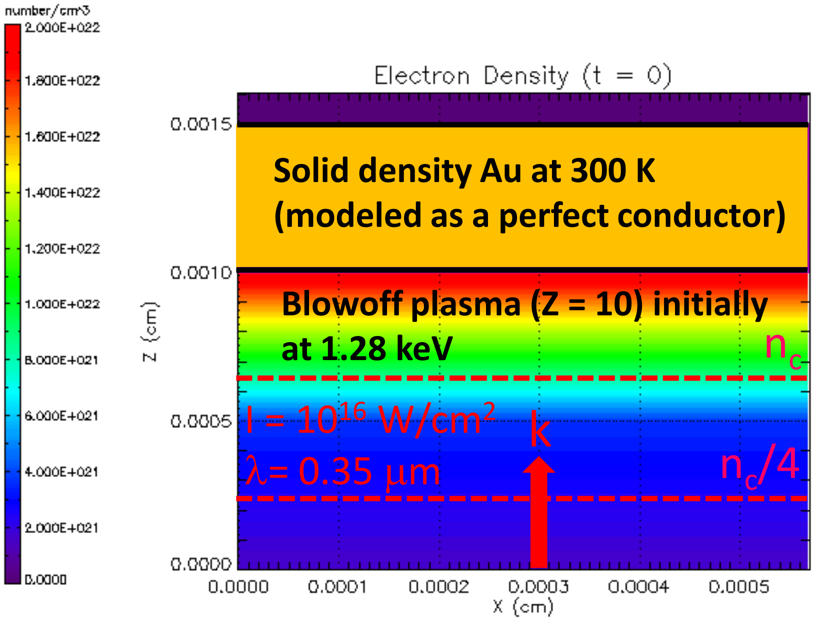
Slow expansion of the ablative plasma occurs on the timescale of a few ns

Radiation temperature profiles for varying laser intensities.

Note: radiation temperature is uniform in the vacuum to the right of the plasma.



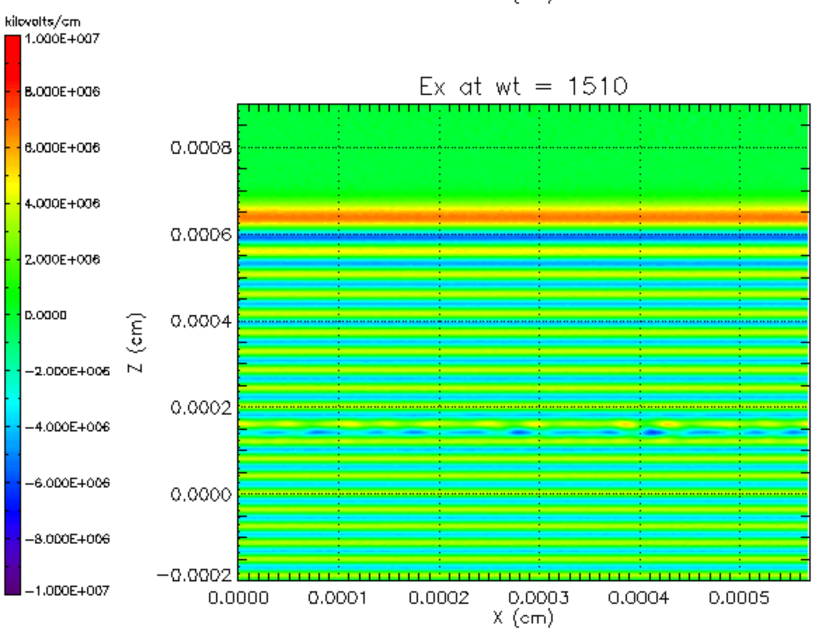
Fully Kinetic Gold LPI Simulation

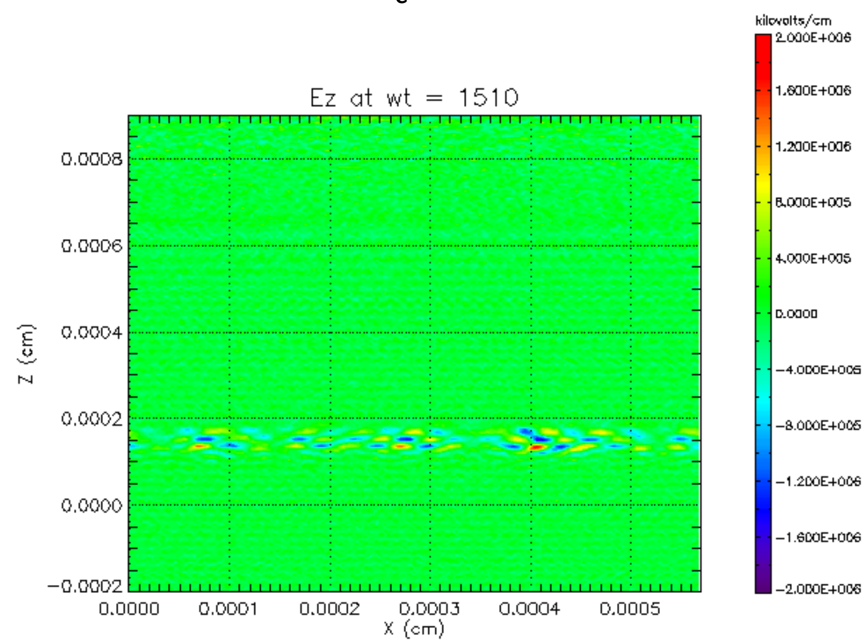


Fully kinetic simulation can capture parametric instabilities, Landau damping, and nonlinear effects for $\Delta x << \lambda$.

Periodic boundaries in x and effectively infinite laser spot size.

Simulation exhibits strong two plasmon decay (TPD) signal at $n_c/4$ surface.





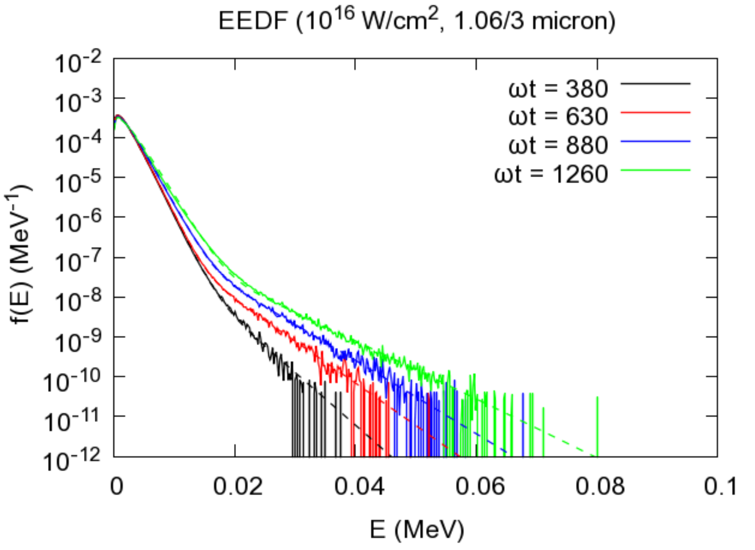
EEDFs from Kinetic LPI Sim: Hot electron production

Electron energy distribution function (EEDF), f(E), calculated in blowoff plasma can be fitted to a bi-maxwellian distribution function.

$$f_{BM}(E) = A_1 f_M(E;T_1) + A_2 f_M(E;T_2)$$

where

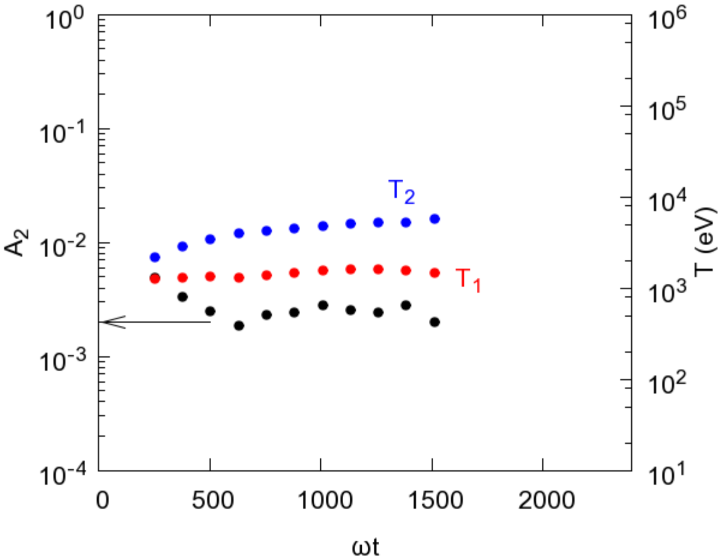
$$f_M(E;T) = \frac{2}{\pi^{1/2}T^{3/2}}\sqrt{E}\exp[-E/T]$$



TPD intensity threshold [1] is given by

$$\left[\frac{I}{\mathrm{W/cm^2}}\right] \geq 5\times10^{12}\,\frac{[T_e/\mathrm{eV}]}{[\lambda/\mu\mathrm{m}][L/\mu\mathrm{m}]}$$

$$L = \left.\frac{n_e}{dn_e/dx}\right|_{n_e \to n_c/4}$$



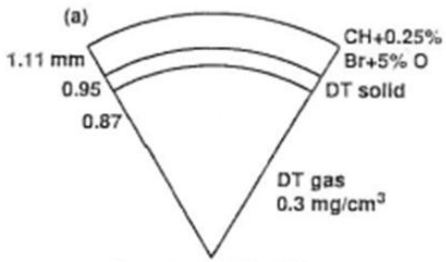
For λ = 0.35 μm and the given plasma parameters, I > 10^{15} W/cm^2 to see TPD.

A parametric study of simulations with varying intensities shows little hot electron production below 10^{15} W/cm^2.

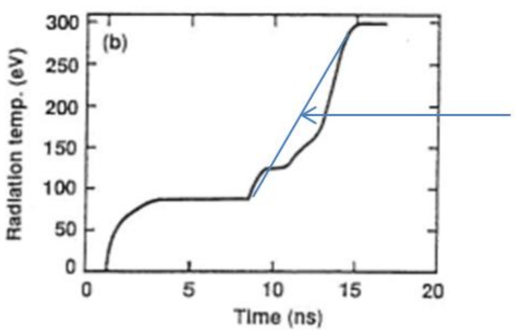
[1] W. L. Kruer, “The Physics of Laser Plasma Interactions”, Westview Press, 2003.

Initial Simulation of NIF Baseline Design [1] with Hybrid Code

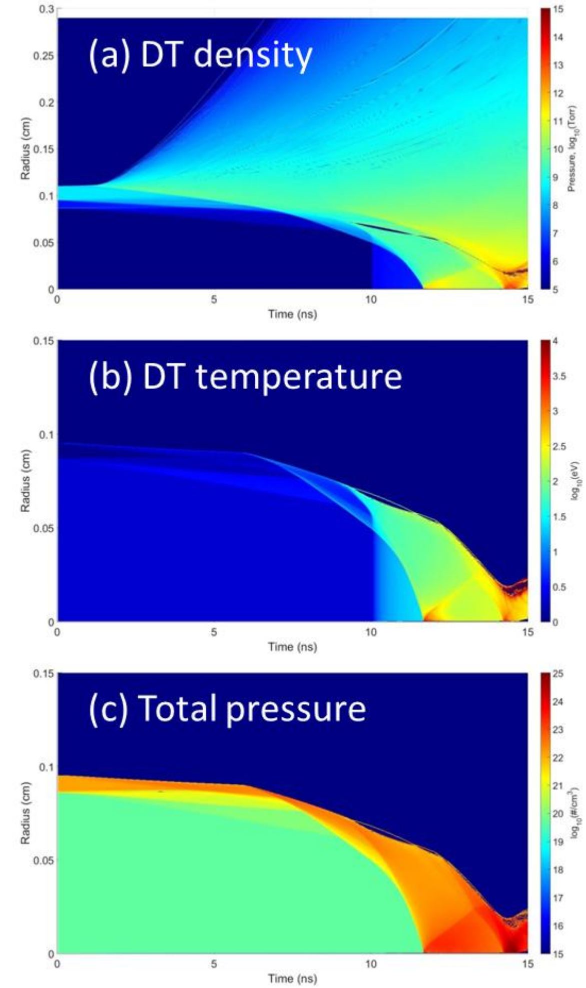
Hybrid simulation of NIF target.
Radiation transport is handled with a single energy group for the radiation diffusion. The fluid model is a PIC Lagrangian technique with a quasi-neutral particle advance.
New simulation capabilities include multiple EOS + application of time dependent radiation temperature on outer surface



In hybrid simulation , pusher did not include 0.25% Br in EOS



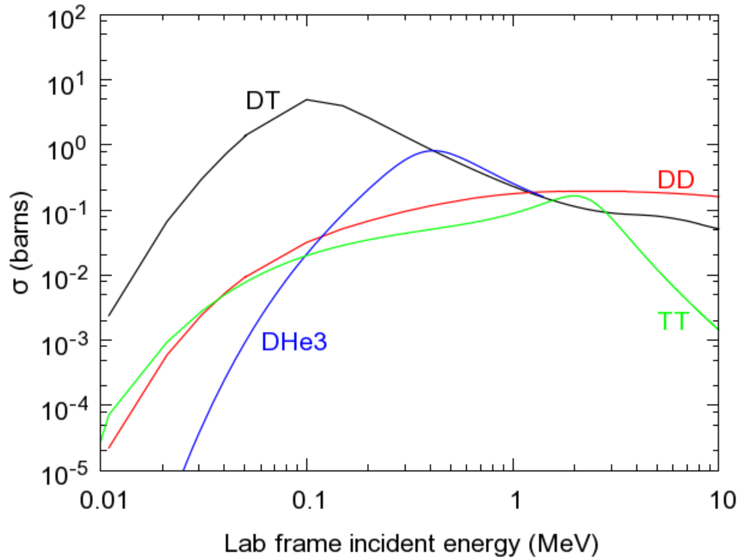
Actual applied temperature in simulation



Initial shock strikes the origin at 11.5 ns, peak fuel compression occurs at 14.2 ns.
Peak velocities approach 4×10^7 cm/s and peak fuel temperatures 10 keV. The total capsule absorbed energy at peak compression is 135 kJ. Comparable to values given in [1].
Next step is to add fusion reactions and kinetic effects to the 1D calculations.

[1] J. D. Lindl, "Inertial Confinement Fusion" (1998).

Binary Fusion Collisions in LSP



The Binary fusion collision model in Lsp now contains the following reactions

1) DD

$D + D \rightarrow T + p$ (Q = 4.03 MeV)

$D + D \rightarrow {}^3He + n$ (Q = 3.27 MeV)

2) **DT**

$D + T \rightarrow \alpha + n$ (Q = 17.59 MeV)

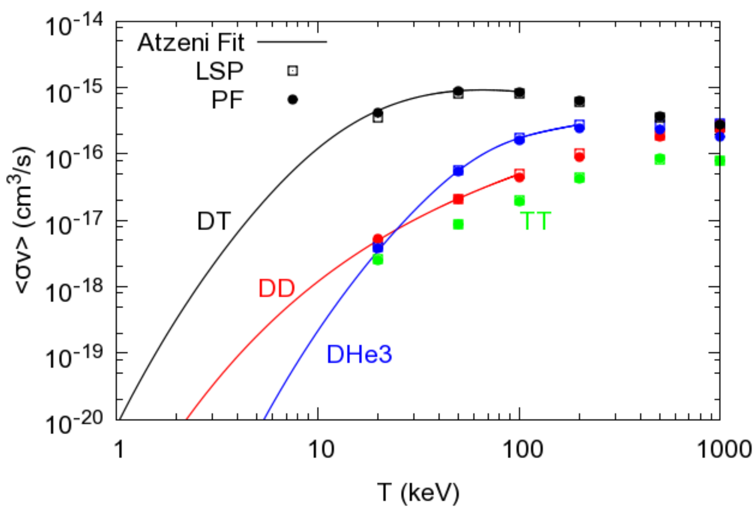
3) **DHe3**

$D + {}^3He \rightarrow \alpha + p$ (Q = 18.35 MeV)

4) **TT**

$T + T \rightarrow \alpha + 2n$ (Q = 11.33 MeV)

Fusion Reaction Rates



Fusion reactivities for thermal plasmas calculated by a series of swarm simulations in Lsp. These results are compared to reactivity fits given in by Atzeni [1] as well as tabulated data given in the NRL plasma formulary (PF) [2].

Note that particle swarm simulations do not calculate good values for reactivities at low temperatures because the reactivity is dominated by the tails of the Maxwellian distribution which are not well sampled by a reasonable particle number per cell.

[1] S. Atzeni and J. Meyer-Ter-Vehn, "The Physics of Inertial Fusion", Oxford University Press, 2004.
[2] J. D. Huba, "NRL Plasma Formulary", NRL/PU/6790—07-500 (2007).

Conclusions/Future Plans

We are pursuing a new first-principles hybrid approach to modeling NIF experiments.

• Our goal is to eventually follow individual particles subject to fully relativistic equations of motion, which will generate self-consistent currents and electromagnetic fields.

• Quasi-neutral fluid description will be used as a fast, approximate solution from which snapshots of inertial or kinetic effects can be turned on.

• Inertial-fluid techniques will be used where appropriate to accelerate the computation.

• Kinetic techniques will be used where non-thermal, finite mean-free-path or charge separation effects are critical.

• Species can dynamically transition from quasi-neutral to inertial fluids to kinetic based on simulation conditions.

•The new computational approach proposed here allows non-Maxwellian particle distributions, finite mean-free-path effects, self-consistent anomalous electrical and thermal resistivities, and charge separation.